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ISBN 978-1-138-00123-7

CRC CRC Press
Taylor & Francis Group
A BALKEMA BOOK

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Safety, Reliability and Risk Analysis:
Beyond the Horizon

Alarm detection in noise work environments: The influence of hearing protection devices

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ABSTRACT: Industrial machines are typical noisy sources causing discomfort and risk to the workers' health. Studying in what extent individual hearing protection devices influences, or not, the perception of alarms in industrial environments and in the presence of background noise was the main aim of this work. The warning signal used was a warning signal from a textile finishing machine and the background noise was produced by a white noise generator. The tests were performed with the subjects in an audiometric booth using different hearing protection devices. The obtained results shown evidence that, under the used test conditions, earplugs and passive earmuffs were the devices showing less interference with the perception of warning signals in the presence of background noise. At the same time it was found that the active (level dependent) earmuffs interfere with the perception of the warning signal in the same conditions.

1 INTRODUCTION

The exposure to high noise levels are a worldwide occupational problem. The recognition that the noise is not a mere annoyance but a serious danger to health is seen today as an increasingly important public health issue (WHO, 2001).

In the United States, in 1990, it was estimated that about 30 million people were exposed to occupational noise levels above 85 dB(A) when compared with more than 9 million people in 1981 (WHO, 2001). In Europe, in 2010, approximately 30% of the workers were exposed to excessive noise levels for at least a quarter of the time of their workday and 7% of European workers suffer from noise-induced hearing loss (PAIR) (MacGoris, 2010).

In an industrial environment there are, most often, a considerable number of machines operating simultaneously thereby producing high levels of noise. This may cause adverse effects to human health both psychological (Edworthy, 1997) and physiological (Nelson et al. 2005) and a barrier to sound and verbal communications (Ganime et al. 2010, Suter 1996a).

Noise Induced Hearing Loss (NIHL), resulting from occupational exposure, is the most common effect on human health, and to reduce this, workers frequently use hearing protection devices (Abel et al. 2002). Hearing protection devices are a specific type of personal protective equipment and should only be used temporarily when waiting for

more effective measures against noise exposure; thus, hearing protection devices should be regarded as a last resort with regard to workers' protection. Nevertheless, hearing protection devices are quite often the first measure to be implemented and are commonly used as a permanent protection measure (Morata et al. 2001). Although hearing protection devices should be a temporary solution in a hearing conservation program, their choice must be carefully thought out and not based on superficial considerations (Arezes & Miguel 2002), and one must take into consideration that the use of personal protective equipment can influence the ability to perform additional tasks such as communicating, detect/discriminate and locate alarm signals (Abel & Spencer, 1999). The alarm characteristics and the attention are also responsible for their perception (Christian, 1999, Suter, 1996b).

Several studies have been made in order to determine the influence of hearing protection devices on speech intelligibility and perception of alarms. Fernandes (2003), for example, conducted a study whose objective was to evaluate the effect of hearing protection devices on speech intelligibility. Also Hashimoto et al. (1996) studied the influence of hearing protectors in the perception of speech in background noise.

The emergency warning systems on industrial machines are considered extremely important because they provide an adequate and timely notice of any situation that may require attention. These alarm signals usually emit loud sounds in order

to be quickly and easily perceived (Lee & Kong, 2006). The referred authors stated that although alarm devices generate extremely high sound and hearing protection devices are the most popular and convenient solution for reducing the perceived sound level, few studies have considered the conjunction with hearing protection.

An auditory danger signal indicates the onset and, if necessary, the end of a dangerous situation. There are two types: auditory warning signals, which require action, and auditory emergency evacuation signals requiring that person(s) must leave the danger zone. A signal reception area is defined as the area in which persons are intended to recognize and react to the signal, and ambient noise is any sound in the signal reception area not produced by the danger signal transmitter. The masked threshold (effective threshold for audibility in noise) is the level of sound at which an auditory danger signal is just audible in ambient noise taking into account the hearing deficiencies of the listeners as well as the attenuation of hearing protection devices (Parsons, 1995).

The current work aims at studying to what extent the hearing protection devices influences the perception of an industrial warning signal, in the presence of background (ambient) noise. Firstly, the influence of each hearing protector device in the perception of the warning signal, in the presence of background noise, was evaluated. Secondly, the differences between each type of hearing protector selected were examined, with respect to its influence on the perception of the warning signal acting in the presence of background noise.

2 METHODOLOGY

2.1 Participants

The selection of the participants was based on the premise that they do not have professional experience in industrial environments, as well as they were not accustomed to the use of hearing protectors devices. It was also important to ensure that the selected group of participants was composed of healthy individuals, regarding their auditory capacities.

As there was no indication of the number of subjects that should form the sample, the minimum number of individuals defined in ISO 4869-1 was considered. This standard is related to testing and cataloging (attenuation) of hearing protection devices and set a minimum number of participants of 16. For ensuring a higher representation, the size of the sample was later increased to 26 subjects.

2.2 Audiometry cabin and noise measurement equipment

An audiometric cabin (OPTAC—Aumec Horprufkabine) was used to simulate the industrial environment in the laboratory and endured similar exposure conditions (Fig. 1). Inside of this cabin, the background noise was emitted through two Sony sound loudspeakers (Model SS-900V-AV) and the warning signal was presented via a wireless speaker (Jawbone-Jambox). Within the audiometric booth, a chair was placed in a way that the test subjects were focused on the booth door. The placement of the chair in this position resulted from the need to place the sound columns for the emission of background noise and the warning signal, in a way that they were at the same distance from the ears of the subject.

The sound level meters used to perform noise measurements, both in the case of background noise as in case of the warning signal, were the Quest Technologies Sound Level Meter—Model 2800 and the Bruel & Kjaer 2260 Investigator.

2.3 Background noise

To determine the background noise in the industrial environment, measurements were performed, with a sound level meter, in the locations where the textile machines were working.

In the laboratory setup, the signal from the background noise was produced with the help of a Bruel & Kjaer sound generator (WB 1314). The noise generator was connected to a Bose filter (802-System Controller C) and the resulting signal was amplified by an Inkel (MA-610). Inside the



Figure 1. Audiometry cabin and sound equipment.

audiometric cabin background noise is evenly distributed across the two Sony columns, i.e. the same level of background noise were delivered by each column. To ensure that the signal generated by the Bruel & Kjaer sound generator was not cut off in the high or low frequencies, a Bose filter was used.

2.4 Warning signal

The warning signal used in this study is a digital copy of the warning signal emitted by a textile machine designated by the common name of mercerizing machine. Whenever this machine starts the process, it emits the alarm twice. The record of the digital copy of the warning signal was performed with the Sony recorder (ICD-UX 200). The resulting sound file was later digitally enhanced to clear all background noise. The total duration of this warning signal is 4 seconds.

To reproduce the alarm in the laboratory setup, the warning signal was emitted through a wireless speaker, placed inside the audiometric booth.

Since the value of the intensity of the warning signal was high and overlapped the background noise, it was necessary to find a level at which the background noise could mask the warning signal and assuring that, at the beginning of the test, subjects did not hear the alarm. Moreover, the warning signal had to be perfectly audible without the background noise. A preliminary test was conducted to determine the value of the intensity of the warning signal.

The wireless speaker providing the warning signal inside the booth was suspended midway through the roof of the cabin, enabling a uniform sound distribution and it was placed 15 cm away from each of the ears of the subjects.

2.5 Hearing protection devices

The criteria taken into consideration for the selection of the hearing protection devices was to select those that are most often used in industry. Regarding the earplugs, it was decided to use the model “Ultratfit 3M EAR”. Regarding the ear-muffs the passive model selected was the “Leight Multi-Position Muff EAR LM-7” and the active model selected was an active (level dependent) device from CeoTronics.

2.6 Test protocol

Each participant underwent 3 tests, one for each different protection conditions (earplugs, passive earmuffs and active earmuffs).

During the test, the background noise was sequentially reduced by 5, 10 or 15 dB and subjects

were instructed to report, by raising their right hand, when the warning signal was audible.

The order in which the tests were carried out was defined during the development of the trial protocol, taking into account that the measurements did not started always with the same protection condition. This precaution prevented a bias effect related to the familiarization of the participant with the test conditions.

3 RESULTS AND DISCUSSION

The sample consisted of 26 subjects (61.5% male) who underwent three tests each, totaling 78 measurements. The average age of subjects was 28 years old and the standard deviation was 6 years old.

The positive responses to the warning signal are presented in Table 1, for each type of hearing protection device, accordingly to the reduction of the background noise. From its analysis it seems that for the earplugs 65.4% of subjects identified warning signal when the background noise was reduced by 10 dB and 30.8% of the subjects positively reported the warning signal when the background noise was only decreased by 5 dB. Only 3.8% of the individuals need a reduction of the background noise by 15 dB to be able to perceive the alarm.

In respect to the passive earmuffs, 50% of the subjects identified the warning signal when the background noise was reduced by 5 dB and the remaining subjects needed a reduction of 10 dB to be able to perceive the signal. Apparently, there was no need to reduce the background noise by 15 dB in order for the warning signal to be perceived with this model of passive earmuffs.

Regarding the active earmuffs it seems that the largest percentage of subjects (57.7%) heard the warning signal when the background noise was reduced by 10 dB. However, 30.8% of the subjects need to reduce the background noise by 15 dB in order to be able to identify the warning signal. For this particular type of active earmuff, only 11.5% of the subjects were able to identify the warning signal when the background noise was reduced by 5 dB.

Table 1. Percentage of positive responses for each type of hearing protector (N = 78).

Hearing protection device	Background noise reduction (dB)			Total
	5	10	15	
Earplugs	30.8%	65.4%	3.8%	100%
Passive earmuffs	50.0%	50.0%	0%	100%
Active earmuffs	11.5%	57.7%	30.8%	100%

From the foregoing, it is possible to conclude that for a reduction of 5 dB, the passive earmuff has a smaller influence on the perception of the warning signal. However, when the background noise is reduced by 10 dB, the hearing protection device that appeared to have a lesser influence on the perception of the warning sign was the earplug. The active earmuff showed the strongest influence on the perception of the warning signal.

The sample considered in this study was evaluated on two characteristics: type of hearing protector and the respective reduction of background noise. The observed frequency of the simultaneous classification of the two features produces a contingency table of two entries with the number of responses that identified the warning signal for each type of hearing protection device and the different levels of reduction of background noise (Table 2).

From Table 2 it is possible to verify a possible difference in the number of responses regarding the use of different hearing protection devices and different levels of background noise. So it became relevant to understand if the reduction of background noise is independent of hearing protection device use ($N = 78$). To achieve this goal, a non-parametric chi-square test was applied, assuming a significance level of 5% ($\alpha = 0.05$).

The statistical analysis performed shows that the reduction of background noise in 5, 10 or 15 dB is dependent of the hearing protection device used ($\chi^2(4) = 19.45, p < 0.05$).

Table 2 also shows, for the active earmuff, a share of 88.9% of responses that they were only able to hear the alarm when the background noise reduced by 15 dB registered of responses, i.e., from the 9 subjects who only heard the warning signal when the background noise was reduced by 15 dB, 8 of them identified the warning signal with the active earmuff and only one person identified with the earplug.

For the passive earmuff it was not observed any case of need to reduce the background noise by 15 dB in order to identify the warning signal.

From the above it can be inferred that the performance of the active earmuffs is significantly

different from the other types of hearing protectors, and their isn't a significant difference between earplugs and passive earmuffs ($\chi^2(2) = 2.72, p > 0.05$). At this point it is important to point out that Arezes & Miguel (2002) found significant differences in the sensation of comfort when comparing earplugs with earmuffs, alongside with a positive correlation between the comfort and the time of effective use of the hearing protector devices.

In a study undertaken by Morata et al. (2001), among the reasons presented by workers for not wearing hearing protector devices, consistently, interference with communication was the one most workers (70%) selected. The second most common reason presented was the fact it interfered with job performance (46%), by making certain sounds from the machinery undetectable.

Fernandes (2003) found that the use of hearing protection devices without ambient noise reduced speech intelligibility considerably in comparison to the condition without protection. Thus, this author stated that in a 'no ambient noise' situation in which only the voice signal was used, the use of hearing protection devices was found to decrease speech intelligibility. This finding applies to the four hearing protection devices models tested by this author, all of which reduced speech intelligibility.

Regarding differences in the type of hearing protection devices, Fernandes (2003) found that the earplugs proved more effective than the earmuffs in improving the intelligibility of speech while providing hearing protection.

4 CONCLUSIONS

Most of the industrial workers are exposed to high noise levels, and frequently use hearing protection devices. Although hearing protection devices contributes to the user's safety, the truth is that workers often complain that the use of protective equipment influences the perception of warning signals (Suter 1996c).

The reduction of perception to warning signals in industrial environments can pose a risk to the exposed persons.

Under the test conditions established and according to the data obtained in this study, it appears that the active earmuffs should be used with some caution in the industrial environments, namely when there is a need to identify an auditory alarm or warning signal. In this type of environment, and in accordance with the results obtained, if workers need to be protected, this protection should be carried out through the use of earplugs or passive earmuffs, as these proved to have the best performance in the tested conditions. This best performance is due to the fact that they interfered

Table 2. Frequency and percentage of the crossed responses for each hearing protector (N = 78).

Hearing protector	Background noise reduction (dB)					
	5		10		15	
Earplugs	8	33.3%	17	37.8%	1	11.1%
Passive earmuffs	13	54.2%	13	28.9%	0	0%
Active earmuffs	3	12.5%	15	33.3%	8	88.9%
Total	24	100%	45	100%	9	100%

less in the perception of the warning signal in the presence of background noise.

In industrial environments, where workers need to use hearing protection devices and, simultaneously, they have also to identify alarm auditory signals it would be important to consider the possibility to carry out training activities for workers so they can develop their hearing sensitivity to warning signals. Therefore, hearing protector devices users could more easily recognize the warning signals and will have more confidence to carry out their tasks. Suter (1996b) states that workers must be informed that the sounds emitted by the machines look different when they wear hearing protection devices and they should be encouraged to get used to the new sound.

Suter (1996b) also suggests the consideration of the installation of a visual (light) signal associated with the audio warning signal to help in a faster identification of the alarm.

Accordingly, the selection of the type of hearing protector device should be carefully considered and training activities for workers should also be undertaken, so they can develop their hearing sensitivity to warning signals.

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